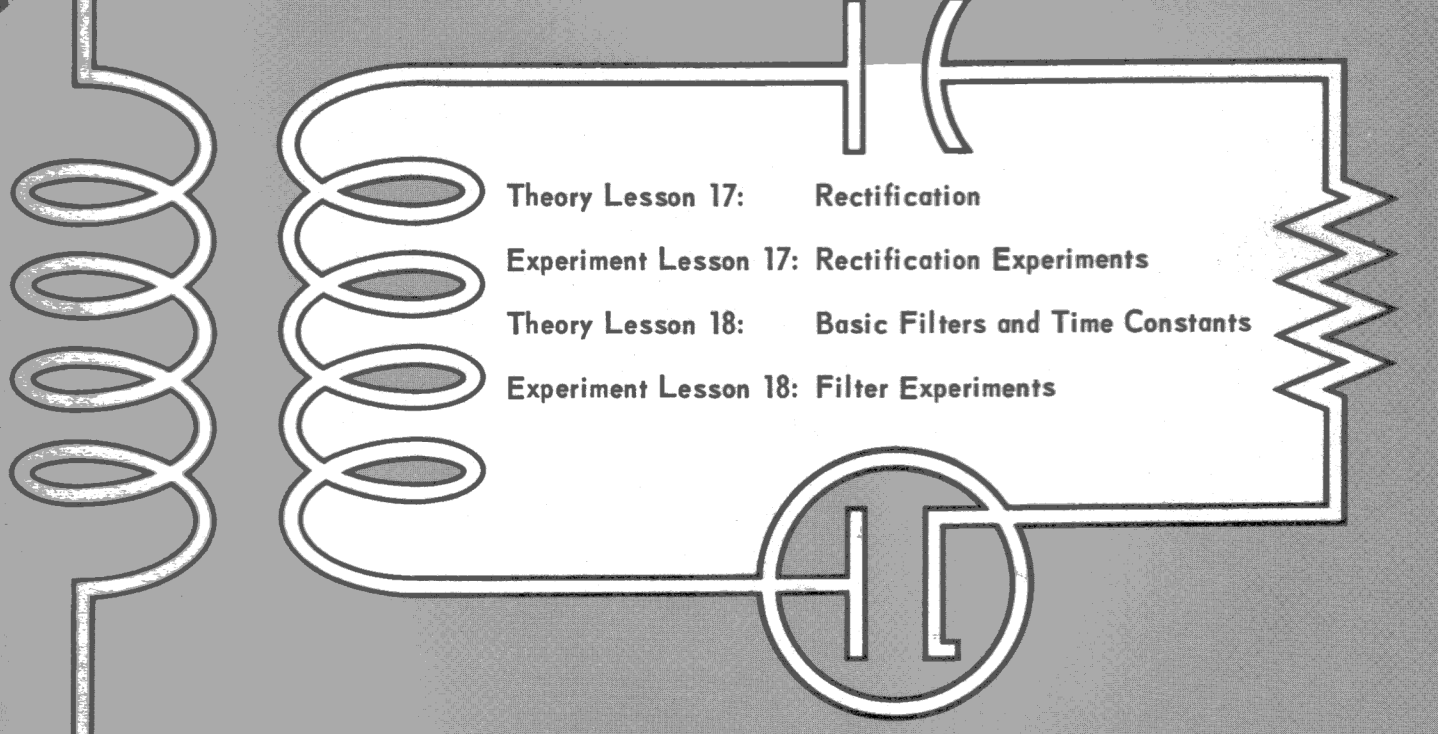


# ELECTRONIC FUNDAMENTALS



Theory Lesson 17: Rectification

Experiment Lesson 17: Rectification Experiments

Theory Lesson 18: Basic Filters and Time Constants

Experiment Lesson 18: Filter Experiments

**RCA INSTITUTES, INC.**

**A SERVICE OF RADIO CORPORATION OF AMERICA**

**New York,**

**N. Y.**



# **ELECTRONIC FUNDAMENTALS**

## **THEORY LESSON 17**

### **RECTIFICATION**

- 17-1. Electron Emission
- 17-2. Diode Structure
- 17-3. Diode Action
- 17-4. Dynamic Diode Characteristics
- 17-5. Rectification
- 17-6. Gas-Filled Diodes
- 17-7. Metallic Rectifiers



**RCA INSTITUTES, INC.**  
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# Theory Lesson 17

## INTRODUCTION

With this lesson, we begin our study of electron tubes. Without electron tubes, radio and television as we know them could not be. But, while radio and television make use of a great share of the electron tubes that are manufactured, few people realize how many tubes are used in other kinds of equipment. It would take several of these pages to tell about the many different ways in which electron tubes serve us. They are used in making phonograph records, transcriptions, and other forms of recording. They are used in the making and showing (projecting) of motion pictures. More and more are used every day in telephone and intercommunication systems. Electron tubes are used in communication with ships, planes, railroad trains, trucks, taxis and mobile police and fire equipment. In industry they are used in control circuits, for heating, and for safety devices. Business machines use many electron-tube circuits. In medicine, x-ray, diathermy, and bloodless surgery would not be possible without electron tubes. Research workers use the electron microscope and computers made with electron tubes. Radar, sonar, and many other defense and navigation aids exist only because of electron tubes.

The electron tubes that we use today result from the work of many men. We can't possibly name them all. However, three men stand out in the early history of the electron tube. Thomas A. Edison, a famous inventor and experimenter, discovered what has since been called the Edison effect. He found that current flowed when he placed a small metal plate inside the glass envelope of one of his carbon lamps (Fig. 17-1) and connected the positive side of a battery to the plate and the negative to the filament. Another scien-

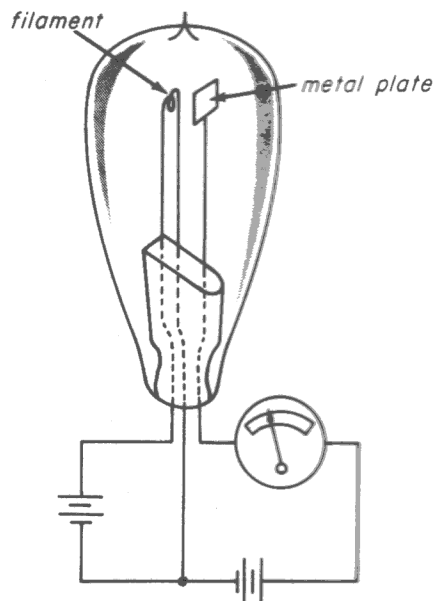


Fig. 17-1

tist, an Englishman named John A. Fleming, found a use for the Edison effect when he made the first two-element radio tube, which he called a valve. The Fleming valve, used as a detector for wireless signals until 1907, was the only form of electron tube known. In that year, Lee DeForest, an American inventor, produced a three-element tube, which he called the Audion. This tube made it possible to amplify weak radio signals so that they might be heard.

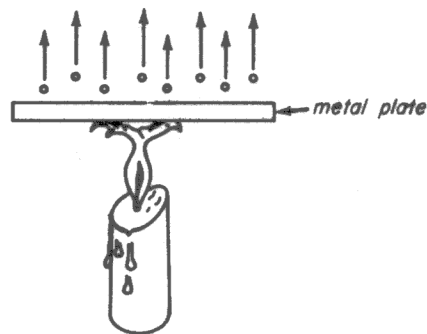
Today there are many kinds of electron tubes that were not even dreamed of at the time the Fleming valve and the DeForest Audion were invented. There are so many that we have several ways of classifying them. One of these ways uses the number of elements to tell one type from another. For example, a two-element tube is called a diode. The diode gets its name from the prefix *di*, meaning *two*. A diode, therefore, has two metal surfaces within the tube, which we might call the main working parts, and to which we connect outside circuits.

The DeForest Audion, because it has three elements, is called a triode, from *tri*, meaning three. In later lessons we will study more complicated electron tube types, such as *tetrodes*, *pentodes*, *heptodes*, and so on. In each case, the name refers to the number of elements in the tube; for instance, the tetrode has four elements, the pentode, five, and the heptode, seven. No matter how many elements a tube has, it operates on the principles to be discussed in this lesson on diodes.

*Rectification*, in radio and television, is the process of changing a.c. to d.c. Any device that is used for this purpose is called a *rectifier*. More electron tube diodes are used to rectify than any other type of rectifier. So, most of this lesson will be about such tubes. However, crystal and metal-film diodes, also used as rectifiers, are also discussed in this lesson.

## 17-1. ELECTRON EMISSION

*Emission* is the act of sending forth. So, *electron emission* is the act of sending forth electrons from the body of the material of which they are a part. As you know, conducting materials, such as metals, have more free electrons than nonconducting materials. At ordinary temperatures, these free electrons move at fast, irregular speeds and in no particular direction. Once in a while, one of these electrons may travel fast enough to escape from the body of the material of which it is normally a part. But only a very few are emitted in this way. One theory says that the free electrons normally remain within the body because the surface of the body tends to act like a barrier and forces the electrons that approach it back toward the center of the body. To break through the surface, an electron must be going so fast that its energy overcomes the barrier force that tends to keep it from breaking through the surface. To produce the conditions in a metal that will increase electron velocity (rate of travel) to the point where electrons may break through the surface barrier, several methods may be used.



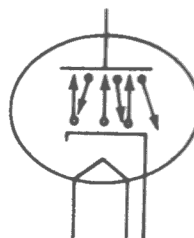
electron emission caused by heat

(a)



photoelectric electron emission

(b)



primary electrons

secondary electrons

secondary emission of electrons

(c)

Fig. 17-2

In your study of electron tubes, you should know something about four types of electron emission. The first of these is *thermionic emission*. Thermionic emission, as shown in Fig. 17-2a, is the sending forth of electrons from a heated body. Heat is the energy used to liberate the electrons. The second is *photoelectric emission* which is the sending forth of electrons from the surface of a light-sensitive material that has been exposed to light rays, as shown in Fig. 17-2b. In this case, light energy causes electron emission. *Cold-cathode emission* is third. It is the forcing out of electrons from a metal surface by bombarding the sur-

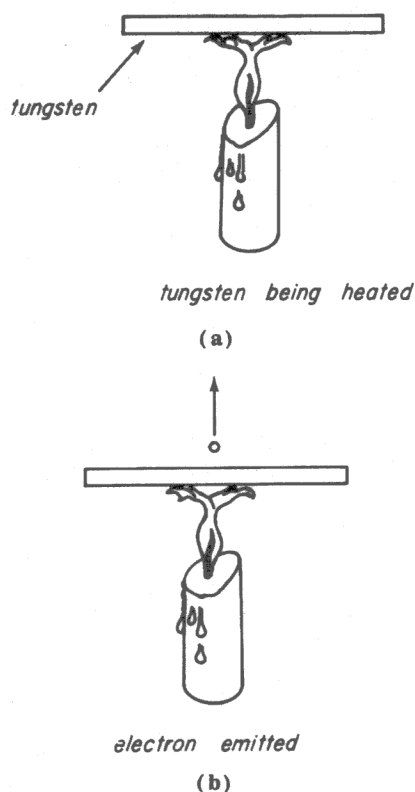


Fig. 17-3

face with positively charged gas particles. The positively charged particles are called ions. The positive ions strike the metal surface and heat it, which increases the electron velocity, and at the same time, the positive charge of each ion acts to pull the electrons through the surface barrier. So, in this case, both heat and electrostatic energy help to free the electron from the metal body. The fourth and last type is *secondary emission*. The first three types of emission are sometimes called *primary emission* to tell them apart from secondary emission. Secondary emission is the forcing out of electrons from a metal surface by bombarding the metal with primary electrons (electrons emitted by a primary emitter), as shown in Fig. 17-2c. This lesson is mostly about electron tubes with thermionic emitters.

**Thermionic Emission.** Let's follow the action of one electron as it leaves the surface of a heated metal. Figure 17-3a shows a piece of tungsten heated by a flame. In Fig. 17-3b, the tungsten is so hot that one electron has left the surface of the metal. We say that the electron is emitted. (In electron tubes, the metal surface that emits electrons

is called the *cathode*, which is abbreviated *k.*) Up until the time that the electron was emitted, the cathode was in a neutral state; it was neither positively nor negatively charged. However, when the electron left the surface of the tungsten cathode, it left the cathode with fewer electrons than it normally has; as a result, the tungsten looks positive to the electron (which you remember is a negative charge). You recall, from your study of electron theory, that unlike charges attract each other. So, the electron is attracted to the heat surface and, if no other charge interferes, the electron will return to the heated cathode.

Suppose at this point we place a positively charged body nearby, as in Fig. 17-4a. Then the emitted electron will have two positively charged bodies acting upon it. Which of the two will attract the electron to it depends on two main factors:

1. The distance of the electron from each of the positively charged bodies
2. The amount of positive charge on each body

Let's see how the position of the electron affects its attraction to either the cathode or the positively charged plate. As shown in Fig. 17-4a, the electron is nearer to the positively charged cathode. If the positive charge on the cathode is equal to the positive charge on the plate, then the electron, being a negative charge, will be attracted more to the cathode than to the plate. (You remember that the farther two charges are from each other, the less is their effect upon each other.) If, however, the electron were nearer to the plate, as in Fig. 17-4b, it would be attracted to that body.

Suppose the electron has come to a dead stop half way between the cathode and the plate as in Fig. 17-4c. Then if two equal and equally distant charges act upon it, the chances are that the electron will stay right where it is. However, if we were to increase the positive charge on either the cathode or the plate, the balance of the forces acting upon the electron would be

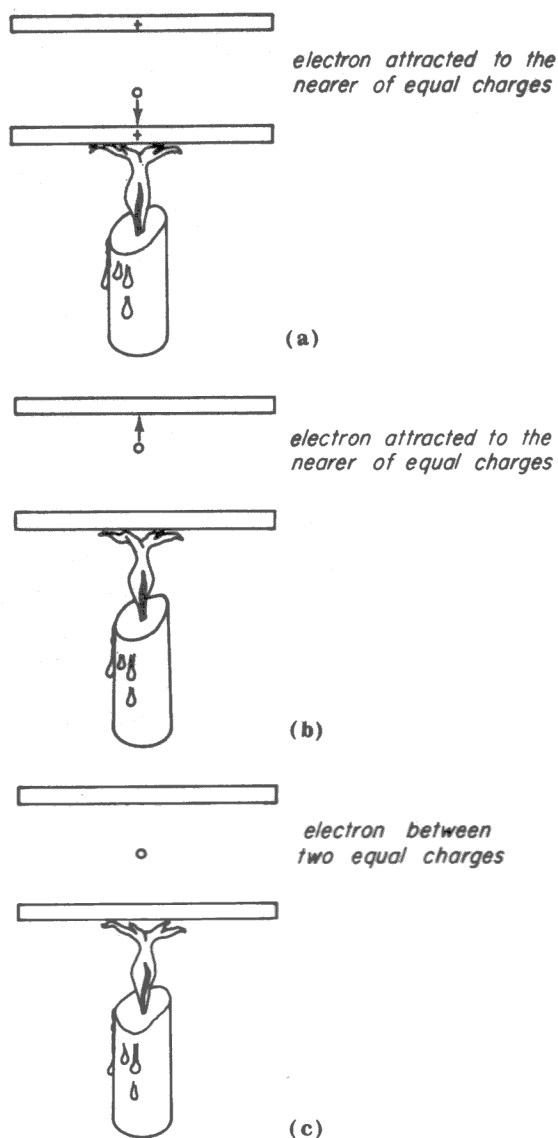


Fig. 17-4

broken and the electron would be attracted to the greater positive charge.

To make sure that the electron will be attracted away from the cathode and toward the plate, all that we have to do is to place a positive charge on the plate that is large enough to overcome the attraction that the cathode has for the electron. To do this, we place a battery between the cathode and the plate, with the positive battery terminal connected to the plate and the negative terminal to the cathode, as shown in Fig. 17-5.

While the electron is attracted toward the plate, there is still one obstacle in the way of the free passage of the electron from the

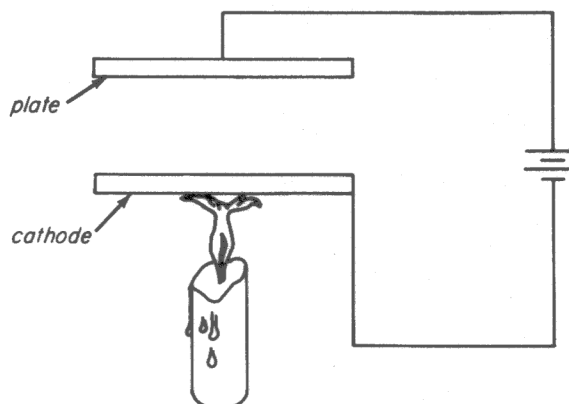


Fig. 17-5

cathode to the plate. The air between the cathode and the plate contains many millions of gas molecules. An electron passing from the cathode to the plate at great speed is likely to bump into one or more of these gas molecules and be prevented from ever reaching the plate. Such accidental collisions can be prevented by placing the cathode and the plate in a glass bulb, as in Fig. 17-6, and pumping out the air. In this way, there will be practically no gas molecules for the electron to bump into.

## 17-2. DIODE STRUCTURE

Until now, we have been using a flame to heat the cathode. Inside a glass bulb, this method is not practical. There are two principal methods used in electron tubes for heating the cathode: direct heating and indirect heating. A *directly heated cathode*, called a *filament*, is simply a wire through which electric current is passed. Heat is

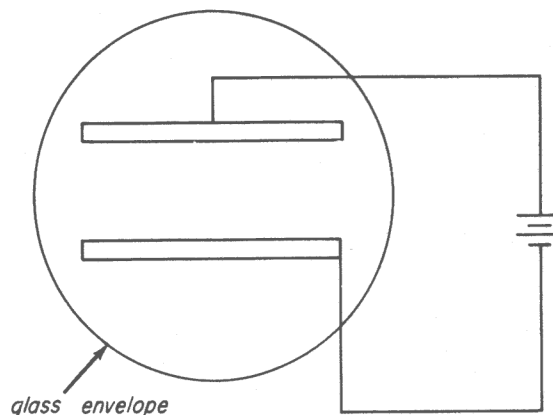


Fig. 17-6

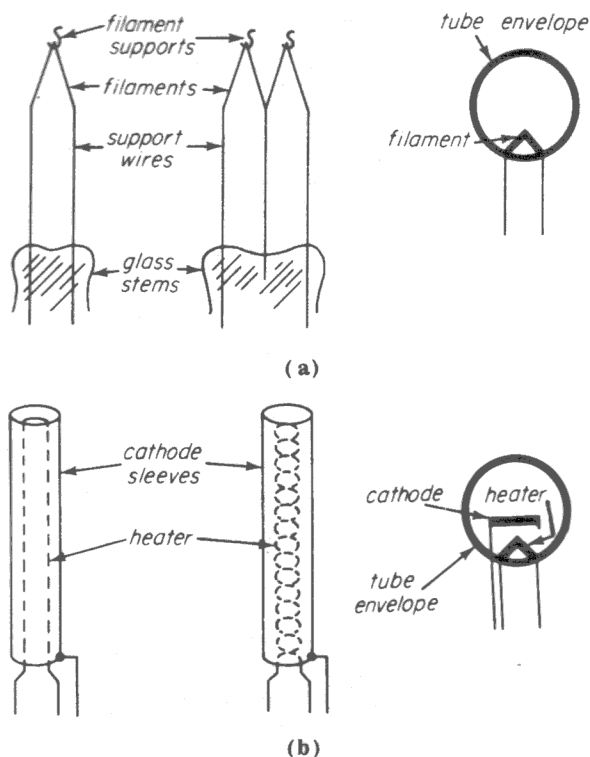


Fig. 17-7

created when the current meets the resistance of the heater wire. Figure 17-7a shows a directly-heated cathode or filament. In the indirectly heated cathode, as shown in Fig. 17-7b, a heater wire is placed inside a thin metal cathode sleeve that is coated with electron emitting materials. The heater wire, usually made from tungsten or a tungsten alloy, is completely insulated from the cathode sleeve and is used only to heat the cathode to the point where electron emission takes place. Although some electrons may be emitted from the heater, these are inside the cathode and serve no purpose; all useful emission is from the cathode. This type of cathode construction has one great advantage — the heater can be operated on alternating current without affecting the operating of the rest of the tube.

The filament in a directly-heated diode is also the cathode, so it is one of the two elements of the tube. The heater in an indirectly-heated diode is separated from the cathode and so is not considered to be one of the tube elements.

**Cathode Materials.** Directly-heated cathodes (filaments) may be made from

tungsten, thoriated tungsten, or an oxide-coated ribbon. Of these materials, tungsten is the strongest, lasts the longest, and takes the greatest overloads without burning out. So tungsten is used for the filaments of the tubes that are used in equipment that must stand up under high voltages, heavy overloads, and rough service. However, tungsten filaments normally operate at temperatures as high as 2,500 degrees centigrade (about 4,500 degrees Fahrenheit).

Tungsten mixed with thorium needs to be heated only to 1,900 degrees centigrade (about 3,400 degrees Fahrenheit) to emit the same amount of electrons. Oxide-coated cathodes need to be heated to between 800 and 1,200 degrees centigrade (about 1,500 to 2,200 degrees Fahrenheit). Thoriated tungsten and tungsten filaments tend to burn away and become thinner and thinner in use, until finally the wire becomes so thin that it no longer can handle the current and so burns out. The oxide-coated filaments of directly-heated cathodes and the oxide coated sleeves of indirectly-heated cathodes are usually made from nickel coated with oxides of strontium and barium. The oxide surface is the actual emitter. While they are more efficient than either tungsten or thoriated tungsten cathodes, oxide-coated cathodes cannot take the overloads and the very high voltages that may be applied to tungsten and thoriated tungsten. For this reason, you will find them used most often in radio and television receivers where overloads and voltages are not great.

The plates, or anodes, of diodes and other electron tubes are made from many different materials such as tungsten, molybdenum, nichrome, graphite, nickel, and tantalum. The material, size, and shape of an anode depend largely on the use to which the tube is put. The design must allow for the cooling of the anode, which must not overheat. (If the anode were to overheat, it would become an emitter, too.) Figure 17-8 shows some typical diode designs; *a* shows a single diode with an indirectly heated cathode, *b* shows two diodes with directly-heated cathodes in the same envelope, and *c* shows two diodes with indirectly-heated cathodes in the same envelope.



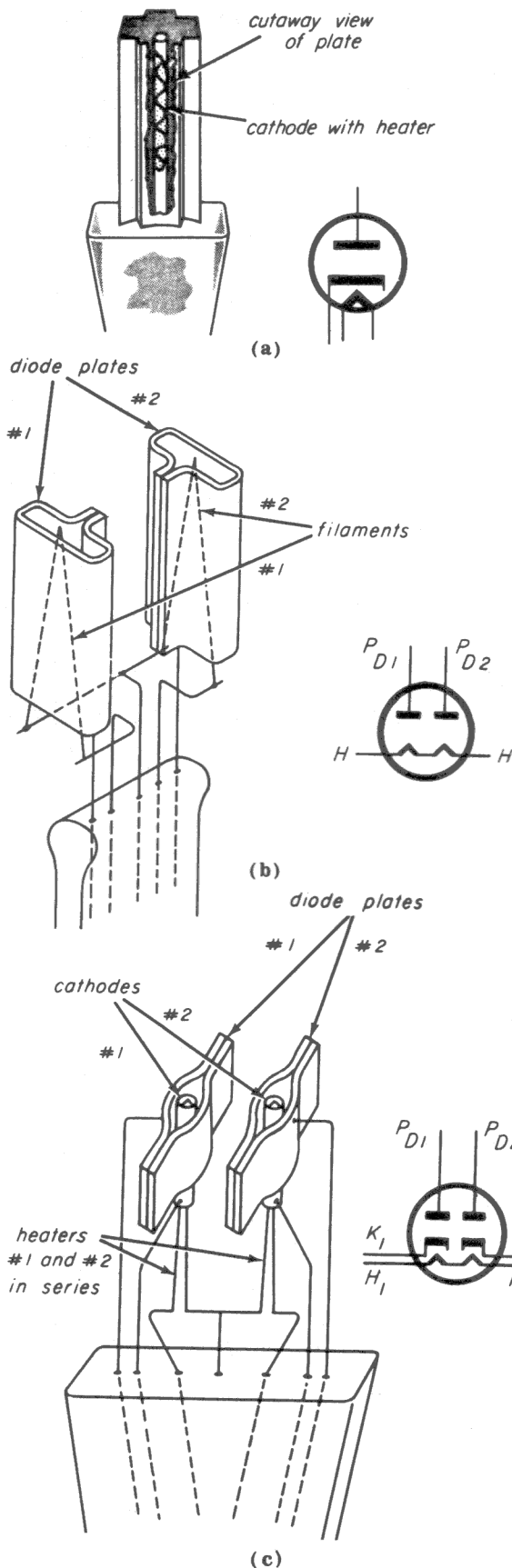


Fig. 17-8

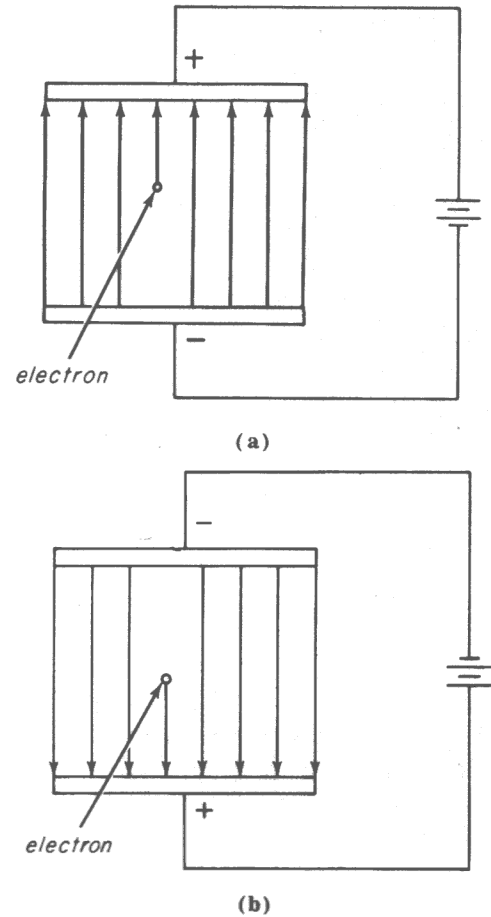


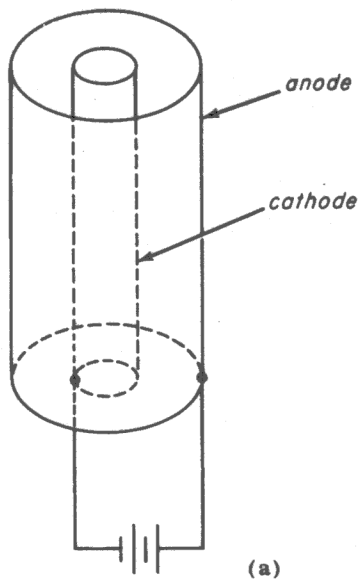
Fig. 17-9

### 17-3. DIODE ACTION

Your study of previous lessons has taught you that like charges repel, unlike charges attract, and when two charged metal plates face each other, as in Fig. 17-9a, an electric field is set up between the plates. A negatively charged particle (such as an electron) placed in this field travels along a line of force in the direction of the line of force (from the negatively charged plate to the positively charged plate). Should the polarity of the charged plates change as in Fig. 17-9b, the direction of electron motion would change, too. These are very important facts because they explain diode action.

What is true of two charged flat plates is equally true of plates that are shaped like those in Fig. 17-10a. An electric field is set up between the cathode and the anode, as shown in Fig. 17-10b. An electron emitted by the cathode would be drawn toward the





anode and would travel in the direction shown. If the polarity of the battery connected to the cathode and anode should be reversed, as in Fig. 17-10c, the electron would be drawn back to the cathode in the direction of the lines of force.

You may wonder why we should care what happens when the charges are reversed. The reason is that we normally apply a.c. to a diode. During one half of each cycle, the cathode is negative with respect to the anode, and during the other half cycle, the cathode is positive with respect to the anode. So, during one half of each cycle, as shown in Fig. 17-11a, electrons travel from the cathode to the anode

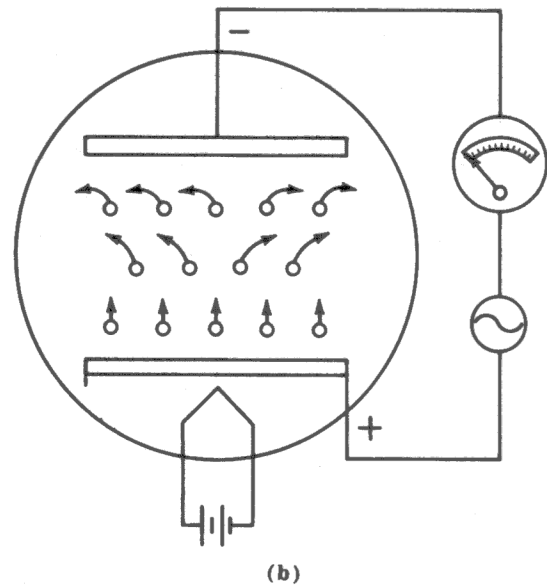
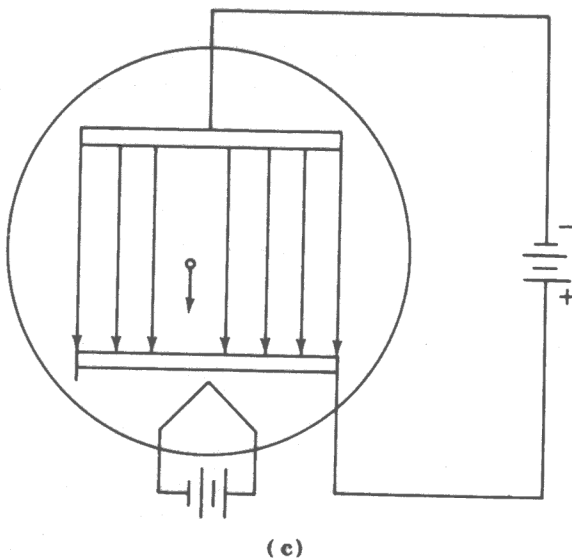
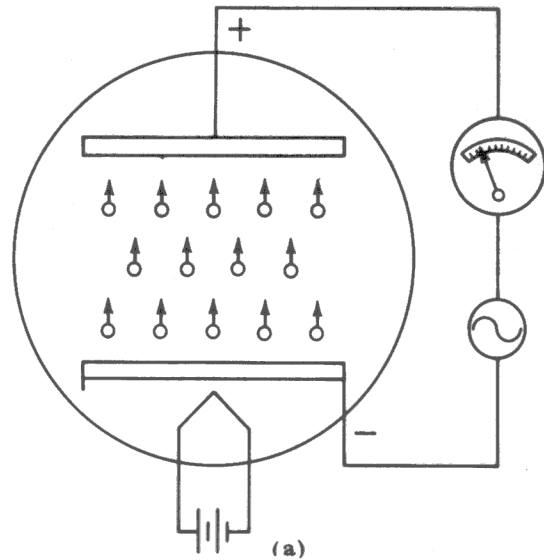
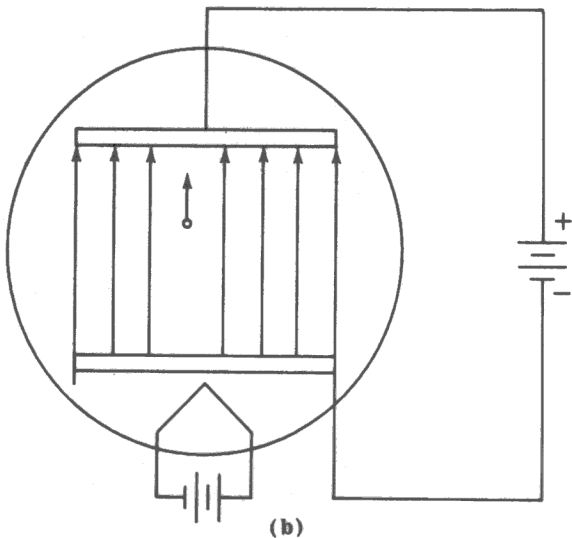


Fig. 17-10

Fig. 17-11

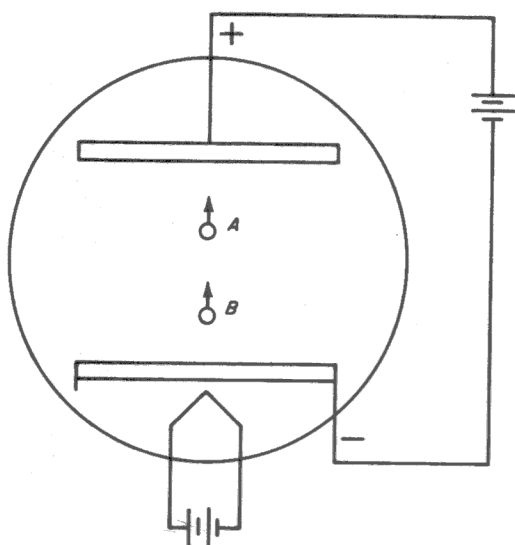


Fig. 17-12

and produce a current flow. During the alternate half cycle, the electrons are repelled by the anode and no current flows (Fig. 17-11b). In this way, the diode acts like a valve — permitting electrons to pass from cathode to anode for one alternation and stopping them from passing during the other alternation. Later, you will see how we use this action.

**Space Charge.** Until now, we have been concerned mostly with watching one electron in the electric field between the cathode and the anode. Actually, of course, a tremendous

number of electrons is emitted by the heated cathode, but for the moment we will look at only two of them, as shown in Fig. 17-12. In the drawing, one of the electrons is marked *A* and the other *B*. We can assume that electron *A* was emitted first and that electron *B* followed immediately after. Both electrons were moving rapidly when they left the surface of the hot cathode. Electron *A* has a clear path as it moves toward the anode, but electron *B* is not in the same position. Electron *B* was going just as fast as electron *A* when it left the hot cathode, but it found electron *A* travelling ahead. You remember that like charges repel each other, so electron *B* is repelled by electron *A*. This tends to slow up electron *B* and may cause it to remain in the neighborhood of the cathode, at least until electron *A* gets out of the way by being drawn to the anode. While electron *B* is out there in space, a third electron, *C*, will leave the cathode and find *B* ready to repel it. When a great many electrons are emitted, instead of just two or three, the force of the positive charge on the anode may not be great enough to attract the electrons as fast as they are emitted by the cathode. As a result, a cloud of electrons will hang in the space between the cathode and the anode. We call this cloud of electrons the *space charge*, because it acts like a negative charge and repels some of the emitted electrons back into the cathode, as shown in Fig. 17-13. As the electric field draws off electrons from the space charge and they travel on to the anode, other newly emitted electrons take their place, so there is a flow of electrons from cathode to anode as long as the anode is positive with respect to the cathode.

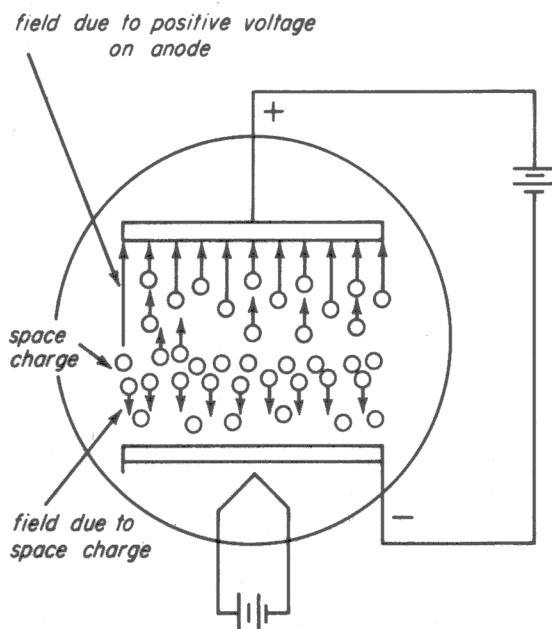


Fig. 17-13

**Current Limiting.** The amount of current in the cathode-anode circuit, as measured by the ammeter in Fig. 17-14, depends on four factors:

1. The temperature of the cathode
2. The type of electron-emitting material used
3. The plate (anode) voltage
4. The space charge

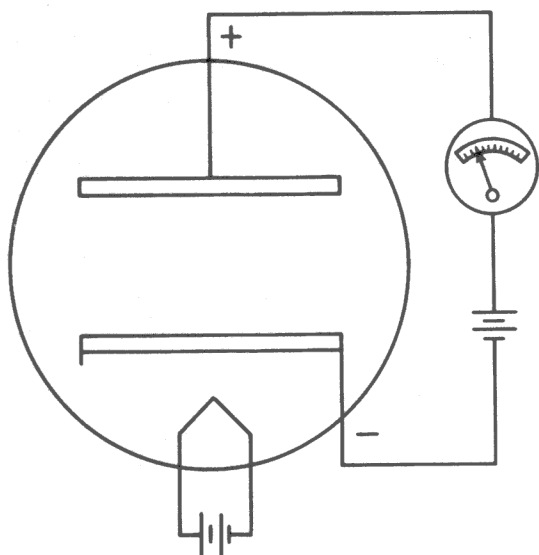
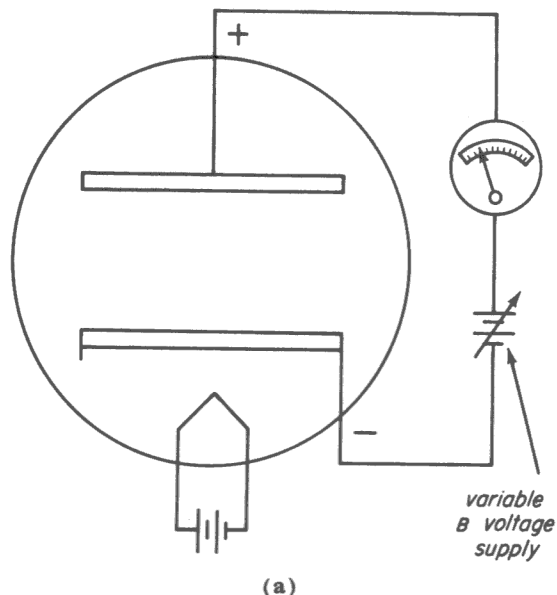


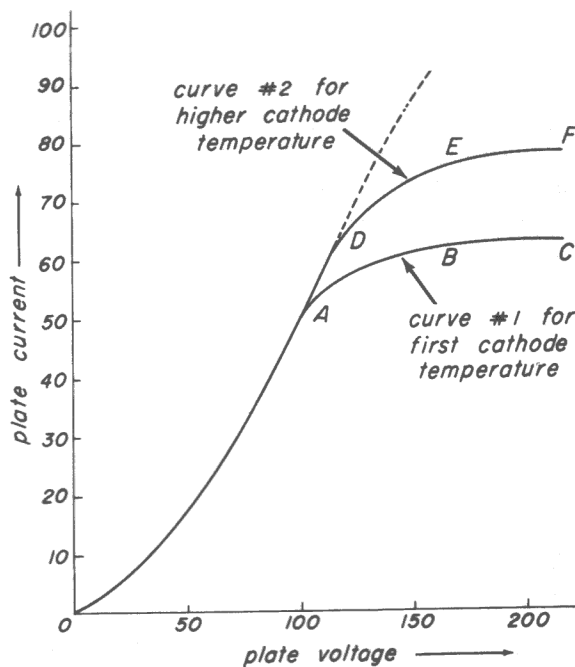
Fig. 17-14

The hotter the cathode, the greater is the number of electrons emitted. The second factor depends partly on the first one and partly on the emitting material. Of course there is a limit to how hot the cathode can get without destroying itself. As the voltage on the anode becomes more and more positive with respect to the cathode, more and more electrons are attracted to it, and so the current (called *plate current*) increases. There is a limit to this current, as you will soon see. You know that the space charge can force electrons to return to the cathode; the greater the space charge, the more are the electrons that are repelled and returned to the cathode. Two types of current limiting result from these four factors: *temperature limiting* and *space-charge limiting*. Let us see how they differ.

**Temperature Limiting.** To see how the cathode temperature limits the plate current let us look at Fig. 17-15a and b. In a, a diode is shown connected to a battery with a variable voltage supply. With such a circuit, it is possible to measure the amount of plate current for different values of plate voltage. The graph in b shows how the plate current ( $i_p$ ) varies as the plate voltage ( $e_p$ ) increases from 0 to 250 volts, while the cathode temperature remains fixed. Looking at the curve through points O, A, B, and C, we see that the value of the plate current rises rapidly with each increase in plate voltage from O until point A is reached. Then



(a)



(b)

Fig. 17-15

the current increases becomes less for each rise in plate voltage until, between points B and C, there is very little increase, no matter how much the plate voltage is increased.

From what we know of diode action, we can see that as the plate voltage increases from zero, more and more electrons are drawn from the space charge, until the plate voltage reaches the point where the plate attracts the electrons as fast as they are

emitted. We call this *plate saturation*, or, sometimes, just *saturation*. When this point is reached, the only way that the plate current can be increased is by increasing the amount of electrons that is emitted by the cathode. This can be done by increasing the temperature of the cathode, as shown in curve #2 through *O*, *D*, *E*, and *F*. With an increase in cathode temperature, more electrons are emitted and the plate current reaches a higher value before saturation occurs. The point to remember is that, in each case, the current is limited by the temperature of the cathode. For this reason, we call it *temperature limiting*.

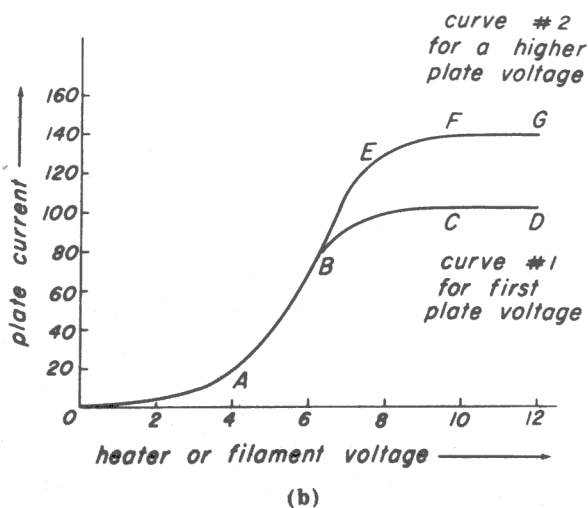
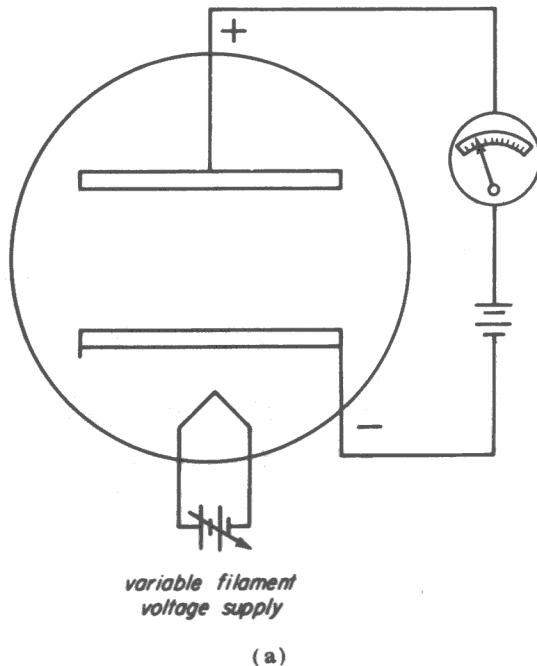


Fig. 17-16

**Space-Charge Limiting.** Now that we know how cathode temperature limits plate current, let's see how the space charge limits it. Figure 17-16a shows a diode with a fixed voltage between the plate and cathode and with a variable voltage supply for the cathode heater. (As the heater or filament voltage rises, the cathode temperature rises.) Figure 17-16b shows what happens to the plate current as cathode temperature is increased and the plate voltage remains the same.

Examining curve #1 through points *O*, *A*, *B*, *C*, and *D*, closely, we see that the plate current rises slowly as the cathode temperature is increased until point *A* is reached, when the current rise becomes very rapid. At point *B*, the rise becomes less rapid until, between *C* and *D*, there is practically no increase in plate current even with an increase in cathode temperature. From our knowledge of diodes, we can see that between points *O* and *B* the plate attracts electrons as fast as they are emitted. However, with further increases in cathode temperature, electrons are emitted faster than the plate can attract them, with the result that the number of electrons in the space charge increases. At last a point is reached where the space charge acts to repel electrons to such an extent that any further increase in electron emission is prevented. Thus, the plate current levels off and does not increase, despite further rises in cathode temperature. We call this point *voltage saturation*. This means that, for a particular plate voltage, the maximum number of electrons has reached the plate and a further increase in current is prevented by the space charge. The only way to increase the plate current is to increase the plate voltage, as in curve #2 through points *O*, *A*, *E*, *F*, and *G*. Therefore, more electrons reach the plate, drawn from the space charge by the greater attraction of the increased plate voltage.

**Diode Characteristic Curves.** The curves that you saw in Figs. 17-15b and 17-16b are called *diode characteristic curves*. When two or more curves on the same graph compare two quantities (like plate voltage and plate current) under different conditions, they are

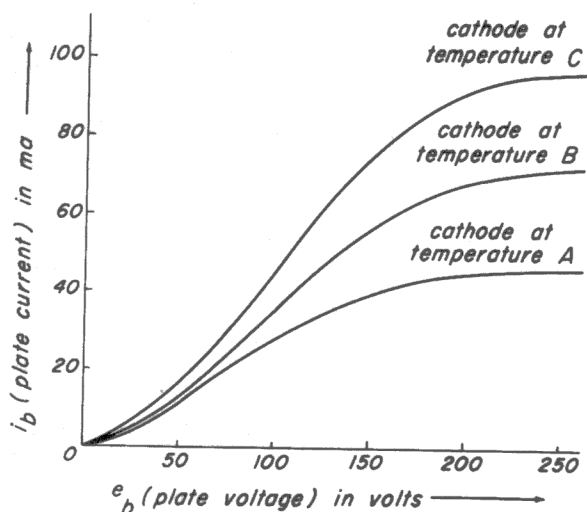


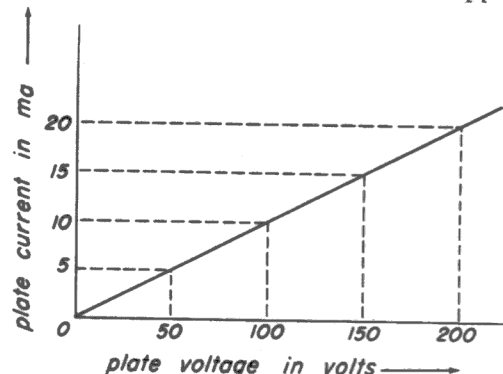
Fig. 17-17

known as a *family of curves*. For example, Fig. 17-17 shows a family of curves for a diode where changes in plate current ( $i_b$ ) are plotted (marked off) against changes in plate voltage ( $e_b$ ). The first curve shows these changes in  $i_b$  for several values of  $e_b$  at a certain cathode temperature; the second curve shows these changes when the cathode temperature is increased to a higher point; and the third curve shows them for a still higher temperature.

Tube characteristic curves are said to be *linear* or *nonlinear*. Let's see what is meant by these terms. Figure 17-18a shows a linear curve. Examine it closely and you will see that for each 50-volt change in voltage, there is a 5-ma change in current. So the changes on the vertical (Y) axis are directly proportional to the changes on the horizontal (X) axis. Figure 17-18b shows a nonlinear curve, where equal changes in voltage do not produce equal changes in current. However, not many tube characteristic curves are completely linear or nonlinear. Instead, most tube curves are like that shown in Fig. 17-18c. The lower portion of the curve, between O and A, is nonlinear, the center portion, between A and B, is for all practical purposes linear, and the upper portion, between B and C, is nonlinear.

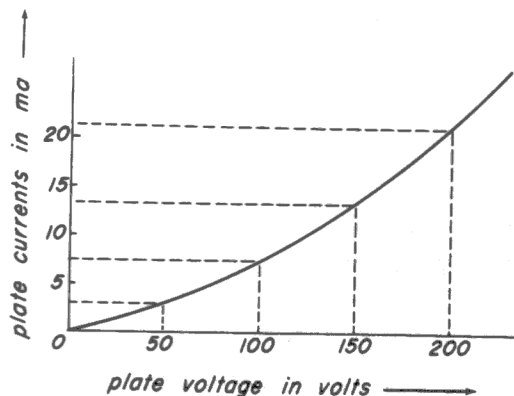
**D-C Plate Resistance.** A diode acts somewhat like a resistor; a plate voltage that is positive with respect to the cathode produces a certain amount of current flow. When the plate voltage is increased, the

current increases, and when the plate voltage is decreased, the current decreases. Therefore, there must be some form of opposi-



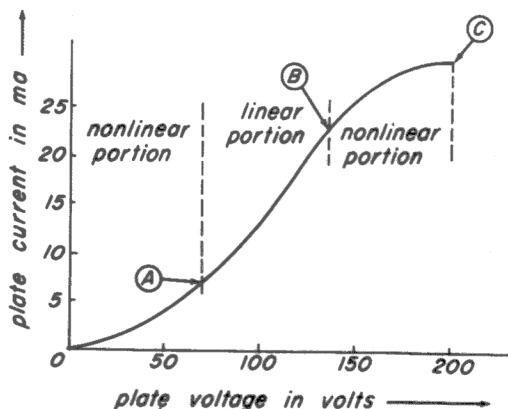
a linear curve

(a)



a nonlinear curve

(b)



a typical tube-characteristic curve

(c)

Fig. 17-18

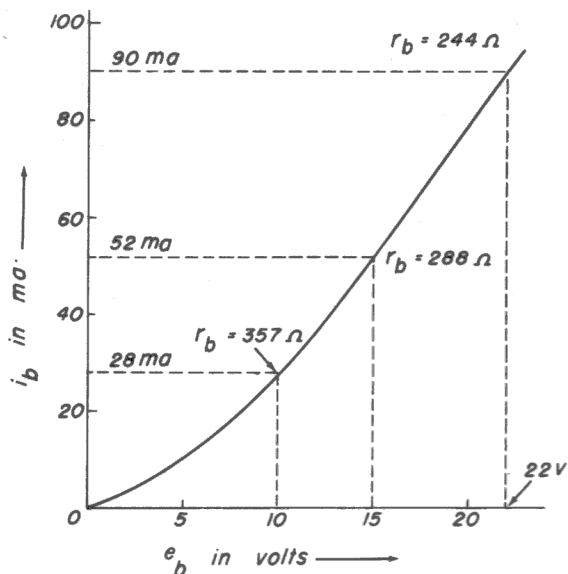


Fig. 17-19

tion to current flow in the tube. This opposition is called *plate resistance* and exists in all types of electron tubes. There are two kinds of plate resistance: *d-c plate resistance* (abbreviated  $r_b$ ) and *a-c plate resistance* (abbreviated  $r_p$ ). D-C plate resistance is the opposition to current flow that the tube offers when d.c. is applied between cathode and plate. To find it, we use Ohm's law — just as we would for any other d-c circuit.

Figure 17-19 shows a typical plate-current (abbreviated  $i_b$ - $e_b$ ) curve for a diode. When 10 volts of d.c. is applied between cathode and plate, the plate current is 28 ma. The d-c plate resistance is found in this way:

$$r_b = \frac{e_b}{i_b} = \frac{10}{0.028} = 357 \text{ ohms}$$

With 15 volts applied between plate and cathode, the plate current is 52 ma, and the d-c plate resistance is found to be 288 ohms.

When 22 volts is applied, the current is 90 ma and the d-c plate resistance is 244 ohms. Examine these figures again and you'll find that the d-c plate resistance decreases as the d-c voltage between the cathode and plate increases.

**A-C Plate Resistance.** The a-c plate resistance is the opposition to the flow of a.c. in a tube whether it be a diode, triode, or any other type of tube. The a-c plate resistance equals a small change in plate voltage divided by the plate current change that it causes. Written as an equation, it is:

$$r_p = \frac{\Delta e_b}{\Delta i_b}$$

where:

- $r_p$  = the a-c plate resistance in ohms
- $\Delta e_b$  = the change in plate voltage
- $\Delta i_b$  = the change in plate current

Figure 17-20 shows the same curve that we used before in Fig. 17-19. To find the a-c plate resistance, we must first select a point on the characteristic curve. (The value of a-c plate resistance that we find will be good for this point only.) Next, we must vary the voltage an equal amount on both sides of this point. The smaller we make this voltage change or *voltage swing*, the more accurate will our calculations be. Let's select 1 volt as the amount we will change the voltage on each side of the point we select on the characteristic curve. Then we will have a total swing of two volts, and  $\Delta e_b = 2$  volts. Suppose we apply this voltage swing at point A on the characteristic curve of Fig. 17-20. At point A, the plate voltage is 10 volts. If we vary this voltage by one volt each side of 10 volts, then the plate voltage will vary from 9 to 11 volts. The current flowing when the plate is 10 volts positive with respect to the cathode is 28 ma. When the plate potential drops to 9 volts the current is 24 ma; and when it

rises to 11 volts, the current is 32 ma. So the current swings from 24 ma to 32 ma, a total of 8 ma. From this we can see that a change of 2 volts on the plate causes a change of 8 ma in plate current. To find  $r_p$  we use the formula:

$$r_p = \frac{\Delta e_b}{\Delta i_b}$$

$$= \frac{2}{0.008}$$

$$= 250 \text{ ohms}$$

If we shift our operating point on the diode characteristic curve to B, we find that the 2-volt swing is between 14 and 16 volts. This causes a current change of 10 ma. The a-c plate resistance is:

$$r_p = \frac{\Delta e_b}{\Delta i_b}$$

$$= \frac{2}{0.010}$$

$$= 200 \text{ ohms}$$

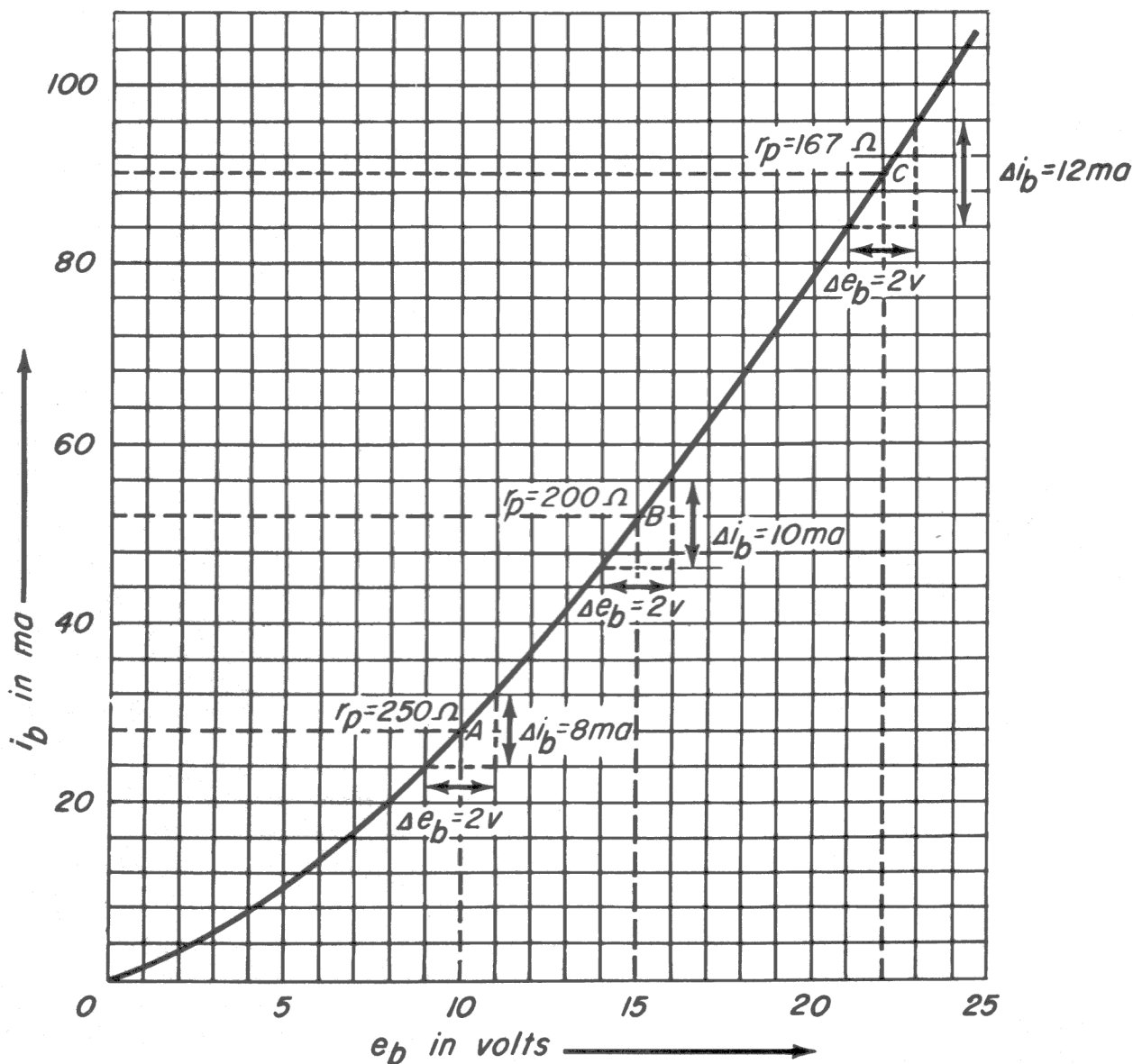


Fig. 17-20



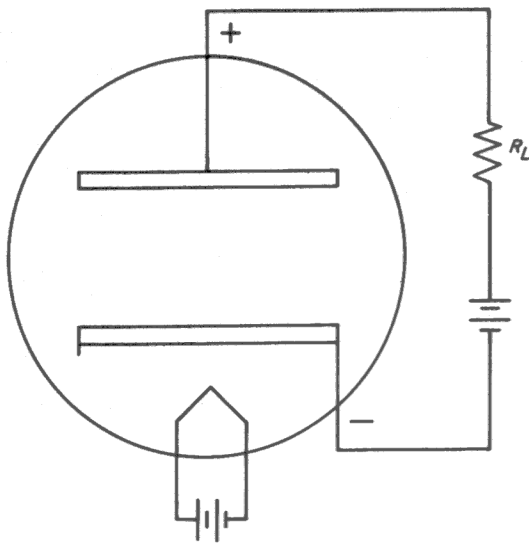


Fig. 17-21

If we shift again, this time to point *C* on the curve, a 2-volt plate voltage swing causes a current swing of 12 ma, and the a-c plate resistance is 167 ohms.

If you compare the d-c plate resistance with the a-c plate resistance, you can see that  $r_p$  is less than  $r_b$ ; this is true for most electron tubes. Just as the d-c plate resistance decreases as the plate voltage increases, so does the a-c plate resistance decrease as the plate voltage at the operating point rises. You can check this by looking again at Fig. 17-20. The plate voltage at the operating point *A* is 10 volts, and the a-c plate resistance is 250 ohms; at point *B*, the plate voltage is 15 volts and the a-c plate resistance is 200 ohms; while at point *C*, the voltage is 22 volts and the a-c plate resistance is 167 ohms.

#### 17-4. DYNAMIC DIODE CHARACTERISTICS

We know that a current can be caused to flow in a diode by heating the cathode so that it will emit electrons and by making the plate positive with respect to the cathode so that electrons will be attracted to it. We have studied the *static* conditions of a diode. Static means stationary. When d.c. is applied to the plate of a diode (or any other tube) and plate current measurements are taken for different values of plate voltage, the conditions are static because the plate-current

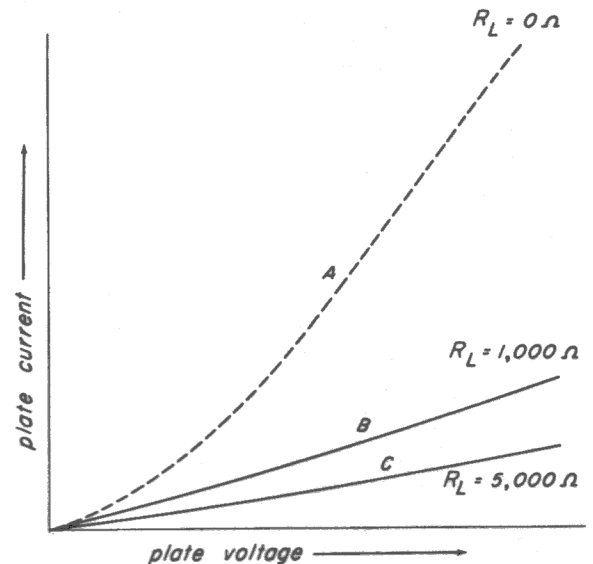


Fig. 17-22

meter reading remains stationary for each value of plate voltage. No work is being done because of the current flow, so we get no value out of it. However, the diode is made so that it can work for us and, if we set up the proper conditions, it will. To put the diode to work, we must supply it with a load. When a load, such as the resistor  $R_L$  shown in Fig. 17-21, is placed in the diode circuit, any current that flows through the diode will flow also through the resistor and produce a voltage drop across it. The voltage drop across the load resistor can be made to be useful to us, as you will soon see.

By placing a load in the diode circuit, we change the operating conditions of the diode. With the load resistor in the diode circuit, the total opposition to current flow is the sum of the tube resistance and the load resistance. When the load resistance is very large in comparison with the plate resistance, the diode characteristic curve flattens out and becomes almost a straight line, as shown in Fig. 17-22. Curve *A* is the static curve that you saw before in Fig. 17-19 and 17-20. Curve *B* shows how the characteristic curve straightens out when the load resistor is 1,000 ohms; while curve *C* shows the characteristic when the load is 5,000 ohms. Curves *B* and *C* represent the *dynamic* characteristic of the tube for different values of load. They are called dynamic because, in producing a voltage drop across the load

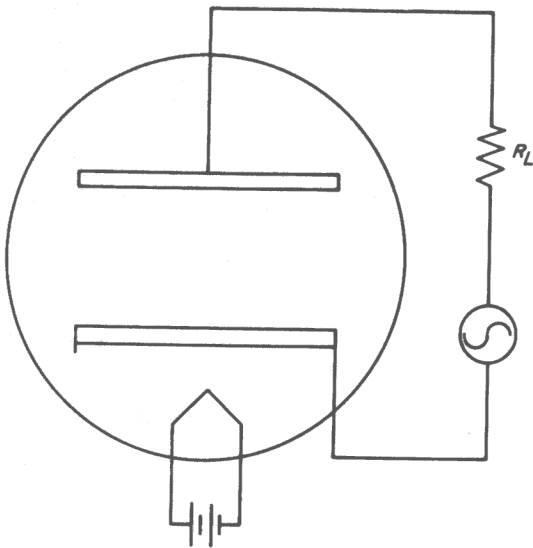


Fig. 17-23

resistor, the diode is working. When a changing voltage, such as a.c., is placed between the plate and cathode of the diode, the output voltage across the diode load will be a changing voltage. From dynamic characteristic curves, it is possible to find out what change in  $i_p$  will occur for each change in  $e_p$  under normal operating conditions (when the tube is loaded).

## 17.5. RECTIFICATION

One of the most important uses of the diode is in *rectification*. Rectification, as used in electronics, means the changing of a.c. to d.c. Suppose we place a sine-wave a-c generator in the diode circuit, instead of a battery, so that between the cathode and plate there is a constantly changing voltage (Fig. 17-23). For convenience, we'll start our study of rectification at that part of the sine-wave cycle when the plate is positive with respect to the cathode. During the first few instants of this alternation there is very little plate current because the plate is only slightly positive with respect to the cathode. However, as the plate voltage increases, the plate current rises because more and more electrons are attracted to the plate. At the peak of the alternation, the plate voltage is maximum and the plate current reaches maximum, too. After this, the generator voltage falls off toward zero and the plate current steadily decreases. At the instant

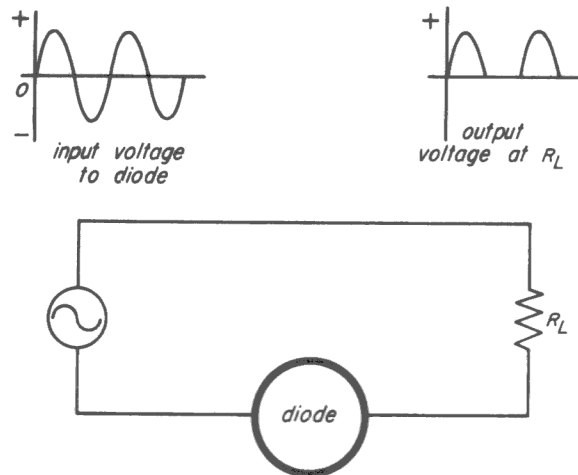


Fig. 17-24

when the generator voltage is zero, there is no difference in voltage between the cathode and plate, and current stops flowing. The plate current remains at zero during the half-cycle when the plate is negative with respect to the cathode. Then, as the next half cycle begins and the plate is again positive with respect to the cathode, current flows once more. So, while the voltage applied to the diode is a sine wave, as shown in Fig. 17-24, the output voltage that appears across the load is a pulsating d.c. that flows only during each half cycle when the diode passes current. This is called half-wave rectification because only half of the input sine wave is rectified.

Figure 17-25 shows a typical unfiltered half-wave rectifier power supply circuit. One side of the high-voltage secondary winding of a power transformer is connected to the diode plate; while the other side of the winding is connected to the diode load resistor, which, in turn, is connected to the diode cathode. At any instant, the a-c voltage,  $e_s$ , that is delivered by the transformer secondary to the diode and diode load is

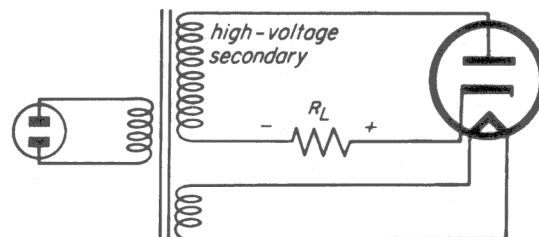


Fig. 17-25

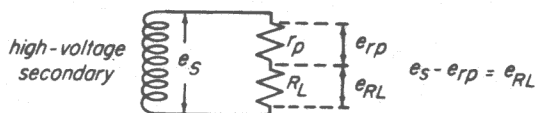
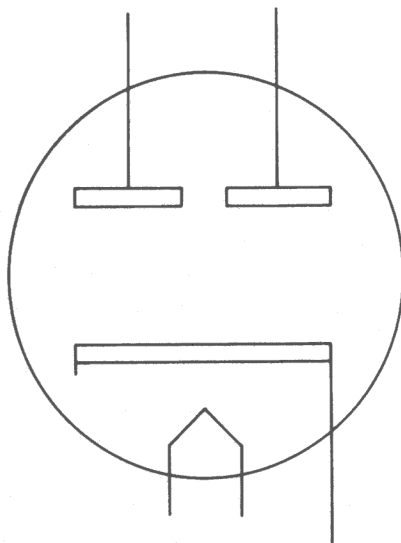


Fig. 17-26

divided as shown in Fig. 17-26. So, the voltage across  $R_L$  at any instant while the tube conducts equals the voltage delivered at that instant by the transformer secondary minus the voltage drop across the tube due to  $r_p$ .

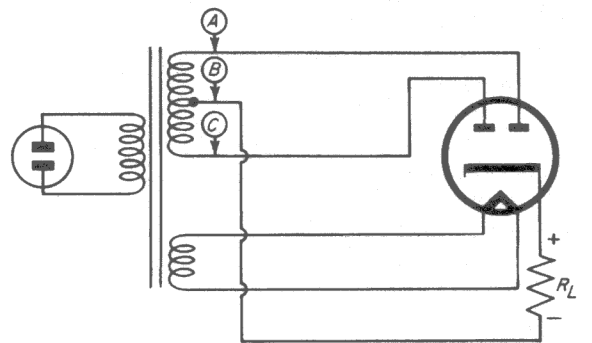
If the voltage delivered by the transformer secondary has an rms (effective) value of 200, the peak value will be about 280 volts ( $1.41 \times 200$ ). If the load resistance is high compared with the a-c plate resistance, the voltage drop across the tube will be small, so that the voltage across  $R_L$  may be as high as 250 volts when the transformer voltage is at its peak. This is an important point that will come up again when you study filter systems and power supplies. Referring to Fig. 17-25, note that the electron flow is from the cathode to plate, down the high-voltage secondary, and then through  $R_L$ . Thus, the cathode end of the load is positive.

**Full-Wave Rectification.** It is possible to rectify both halves of the sine wave by using two diodes. In most cases, the two diodes are contained in the same glass envelope, as in Fig. 17-27. Such a tube is called a *duo diode*, a *twin diode*, or a *full-*

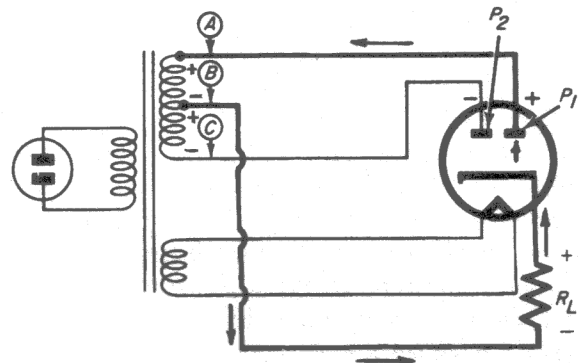


a twin diode

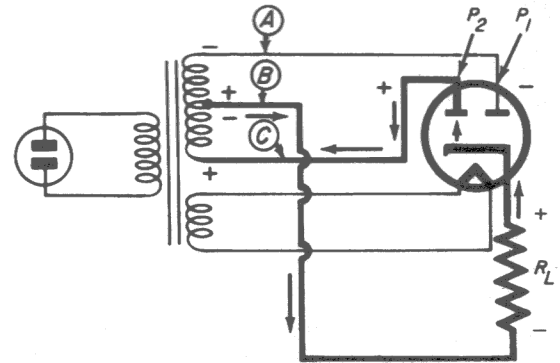
Fig. 17-27



(a)



(b)



(c)

Fig. 17-28

*wave rectifier.* The tube shown in the drawing has an indirectly-heated cathode. Figure 17-28a shows a typical full-wave rectifier circuit, such as will be used in the power-supply section of your receiver. Here the high-voltage secondary is center-tapped, with the end terminals going to the diode plates and the center tap being connected to the load resistor, which, in turn, is connected to the cathode. Let's follow the operation of a full-wave rectifier through one complete cycle of the input a.c. We'll start, as in Fig. 17-28b, when the A end of the high-voltage secondary is positive with respect

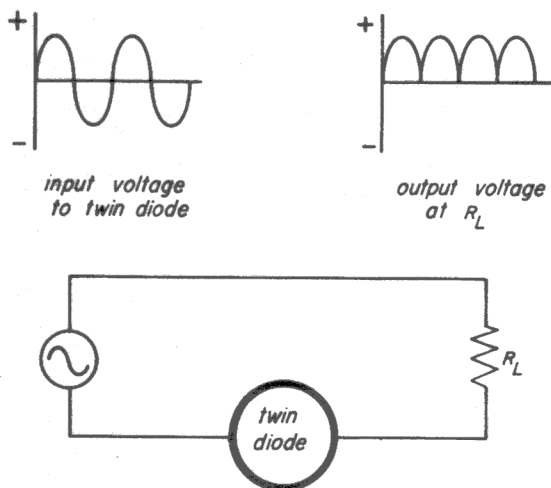


Fig. 17-29

to  $B$  (the center tap) and  $B$  is positive with respect to  $C$  (the other end of the secondary). Because plate  $P_1$  is positive with respect to the cathode, current flows from the cathode to plate  $P_1$ , through the high-voltage secondary from  $A$  to  $B$ , then through the load resistor back to the cathode. While current is flowing through this diode, the plate of the other diode is negative with respect to the cathode and so it does not conduct. During the second half-cycle, shown in Fig. 17-28c, when the  $C$  end of the high-voltage secondary is positive with respect to  $B$ , and  $B$  is positive with respect to  $A$ , no current flows from the cathode to plate  $P_1$  because the cathode is positive with respect to this plate. However, plate  $P_2$  is positive with respect to the cathode, so current flows from the cathode to  $P_2$ , through the high-voltage secondary from  $C$  to  $B$ , then through the load resistor back to the cathode.

Because the current flows through the load resistor in the same direction during each half cycle, the polarity of the voltage across the load is always the same, the cathode end being positive. The voltage into the full-wave rectifier is sine-wave a.c., and the voltage across the load resistor is pulsating d.c. with a pulse for each sine-wave alternation, as shown in Fig. 17-29.

## 17-6. GAS-FILLED DIODES

Most of the air is pumped out of the tube when it is made. Then, to make sure that the vacuum is as complete as possible, a small

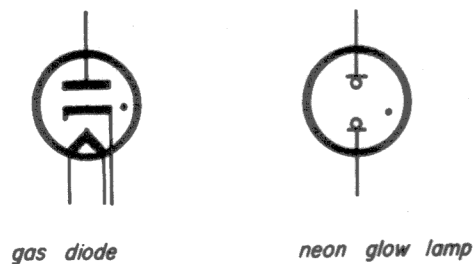


Fig. 17-30

amount of magnesium or barium is flashed (set on fire) within the tube to burn up any gases that remain. Such a tube is called a *hard tube*. Such high-vacuum tubes do not pass high currents. Where a rectifier must pass high current, it is filled with a gas such as argon, neon, nitrogen, or mercury vapor. Gas-filled tubes are low-vacuum tubes and are called *soft tubes*. Figure 17-30 shows the schematic symbols for two types of gas diodes.

**Ionization.** The electrons that travel to the plate to produce plate current come from two places: the heated cathode and the gas molecules. The action is as follows. Electrons leaving the cathode at high speed bump into gas molecules and cause the molecules to lose one or more electrons. These electrons join the stream of electrons traveling toward the plate. The gas molecules that have given up electrons are said to be *ionized* and are called *positive ions*. The positive ions move toward the cathode (unlike charges attract) and attract electrons from the space charge, which permits the cathode to emit more electrons. Such a tube permits the flow of very high currents; therefore it has a very low plate resistance.

**Firing Point.** Electrons must travel at a very high rate in order to remove other electrons from the gas molecules. The higher the potential difference between the plate and cathode, the greater is the velocity of the electrons. Before *ionization* (the process of removing electrons from the gas molecules) can start, the voltage between the plate and cathode must reach a certain minimum amount, which is called the *ionization potential* or *firing point*. Once ionization starts, the action continues even if the plate voltage falls below the firing point.

However, as the plate voltage decreases, a point is reached where ionization stops. This is called the *deionizing* or *extinction potential*.

**Cold-Cathode Diodes.** A *cold-cathode* diode has a cathode that is heated by being bombarded by positive ions. The tube is so designed that when the plate-to-cathode potential is high enough, the gas becomes ionized. The ions strike the cathode and heat it to the point where it starts to emit electrons. From then on, it acts like any other gas-filled diode. Because the cathode is not heated in the usual way, ionization is not started by electrons emitted by the cathode. However, gas-filled tubes always have some ions, due to the action of light and cosmic rays, that are called *residual ions*. These residual ions require a greater striking potential than is needed for hot-cathode gas diodes.

Cold-cathode diodes are seldom used as rectifiers. There is listed in your RCA Tube Manual: a full-wave rectifier, OZ4. However, glow tubes and lamps receive more use in radio, television, and other electronic circuits. For example, neon lamps and bulbs have electrodes of the same size and shape, so either may act as a cathode and emit, and either may act as the plate and receive electrons. A neon bulb, such as shown in Fig. 17-31, will conduct in either direction. If a d-c voltage as high or higher than its striking potential is placed across the terminals of the neon glow lamp, one electrode

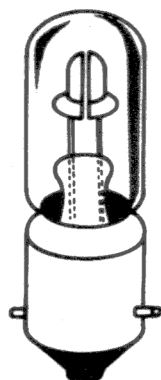


Fig. 17-31

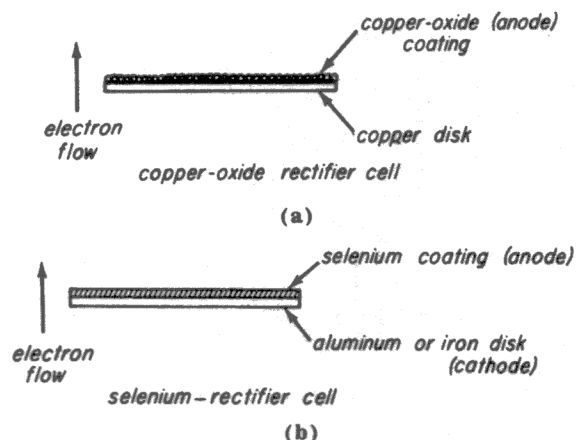


Fig. 17-32

will emit and glow and the other electrode will act as the plate. If the polarity of the connections is reversed, the cathode becomes the plate and the plate becomes the cathode. When placed in an a-c circuit, both electrodes glow because each acts as a cathode on alternate half cycles. Perhaps you can see why neon lamps are used to test the polarity of d.c. and to identify a.c. and d.c.

The voltage across an ionized glow tube, or *glow-discharge* tube as it is sometimes called, remains the same even if the current varies. For this reason, such tubes are used to regulate voltage in power-supply circuits. When you study power supplies, you will learn more about them.

## 17.7. METALLIC RECTIFIERS

Until now, we have discussed only electron-tube diodes. However, there are two basic kinds of diodes that rectify without using the electron tube principle. The first of these is called a *metallic rectifier* and the second is called a *crystal diode*. We will discuss metallic rectifiers first. The basic unit or cell of one type of metallic rectifier is made from a copper disk coated on one side with copper oxide. This rectifier cell, shown in Fig. 17-32a, offers low resistance to the flow of current from the copper cathode to the copper-oxide anode but offers high resistance to current flow in the reverse direction (from the copper oxide to the copper). Another basic rectifier cell

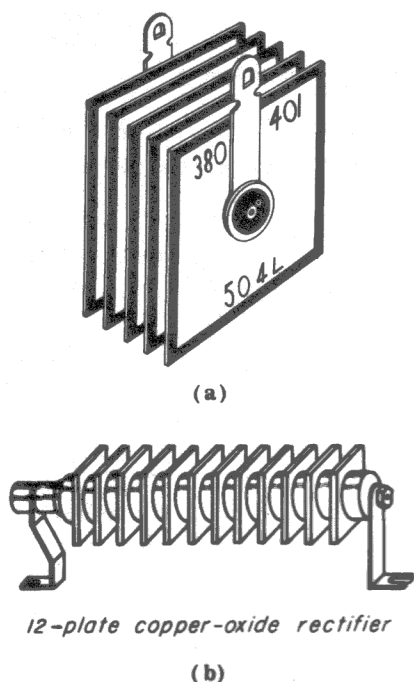


Fig. 17-33

is a disk of aluminum or iron coated on one side with selenium. This rectifier, shown in Fig. 17-32b, offers low resistance to the flow of current in the *forward* direction (from aluminum or iron to selenium).

The copper-oxide or selenium coating can withstand a limited voltage without breaking down. The safe operating voltage for a copper-oxide rectifier cell is 11 volts and for a selenium cell is 26 volts. When it is necessary to rectify higher voltages, cells are stacked together, as shown in Fig. 17-33a. Five selenium cells stacked together can safely withstand 130 volts. Such rectifiers are widely used in the power-supply circuits of a.c.-d.c. and 3-way portable radio receivers. However, it would take 12 copper-oxide cells, as shown in Fig. 17-33b, to produce a rectifier that could withstand the same voltage as the 5-cell selenium rectifier. Between each copper-oxide cell is a soft-metal (usually lead) disk. The purpose of the disks is to make contact with the oxide coating (anode) and to allow air to reach the copper-oxide disks for cooling.

Figure 17-34a shows a metallic rectifier used as a half-wave rectifier. The circuit is the same as for any other diode. Notice

that the actual electron flow is opposite the direction of the arrow part of the metallic rectifier symbol. Figure 17-34b shows two metallic rectifiers used in a full-wave rectifier circuit that uses a center-tapped high-voltage secondary, while Fig. 17-34c shows a bridge-type circuit that uses four rectifiers.

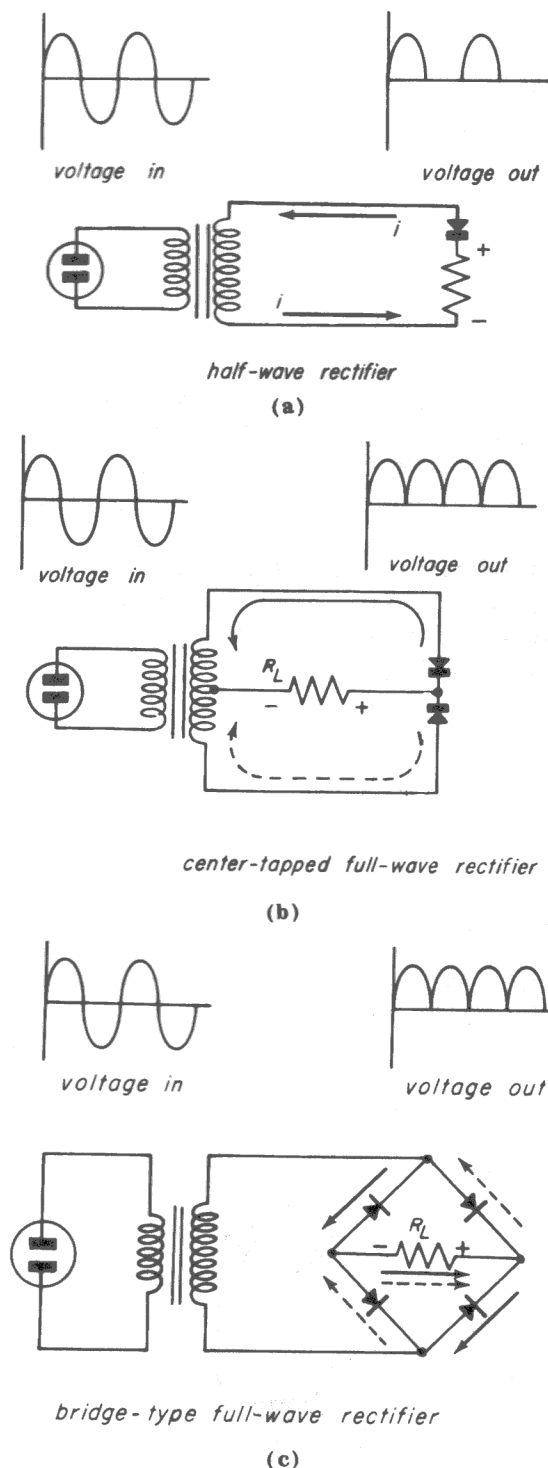


Fig. 17-34

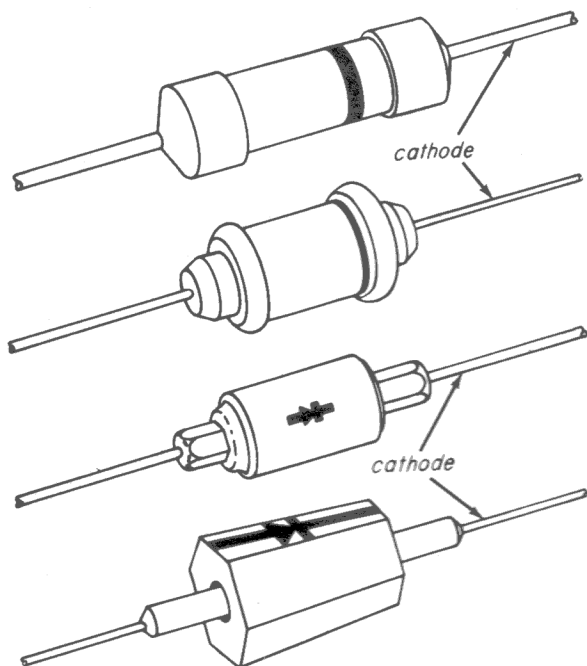


Fig. 17-35

The unbroken arrows show direction of current flow for one half cycle and the broken arrows for the second half cycle.

**Crystal Diodes.** Another diode that acts in much the same way as a metallic rectifier is the *crystal diode*. Certain crystal substances such as germanium, silicon, and others offer a low forward resistance to current flow and a very high *back* resistance to current flow in the opposite direction. The crystals that rectify a.c. in your multimeter are of this kind. Figure 17-35 shows some typical crystal diodes. Manufacturers differ in the way they mark the cathode terminal of a diode crystal; however, most manufacturers use one or more of the markings shown in Fig. 17-36 to identify the cathode terminal. Note that the cross bar and not the arrow represents the cathode.

While crystal diodes act like metallic rectifiers, they are made differently. A cross-section view of a typical crystal diode is shown in Fig. 17-37. The two diode elements of the crystal are the cat whisker (anode) and the crystal (cathode). Current flows freely in the forward direction (crystal to cat whisker) and is minimum in the back direction (cat whisker to crystal). The crystal most often used is germanium. The

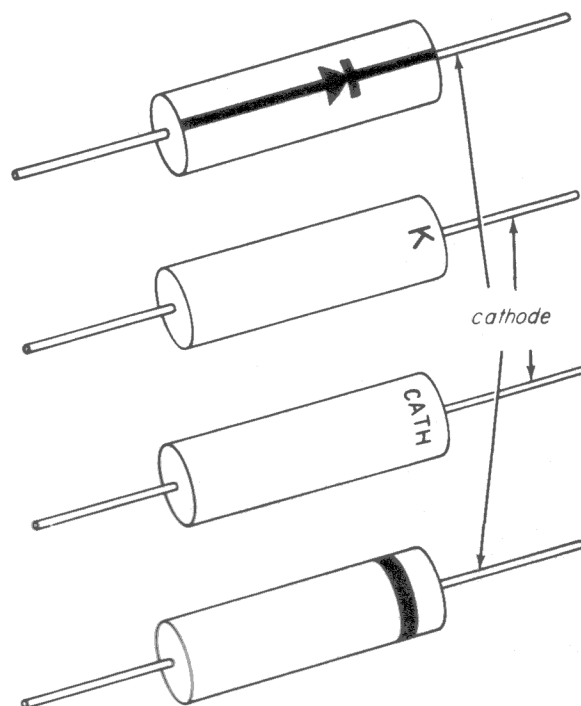


Fig. 17-36

cat whisker, made from tungsten welded to a nickel pin, is S-shaped so that it presses against the crystal for good contact. Crystal diodes are commonly used in multimeters to rectify a.c. to the d.c. that the meter movement was designed for. They are used as detectors in radio receivers and in some television frequency-control circuits. The average current capacity of crystal diodes varies from about 20 to 60 ma. Because they are limited to relatively low currents, crystal diodes are not often used in rectifier circuits of power supplies. However, when they are used, the space needed for the rectifier is very small indeed.

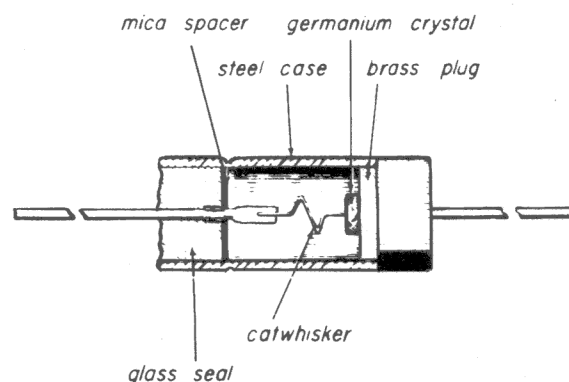


Fig. 17-37